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Spectrum Stretching: Adjusting to an Age of Plenty

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ABSTRACT:
This paper shows--contrary to popular opinion--that spectrum crowding should decrease in the future. The causes of this decrease include the development of spectrum-efficient technologies like digital compression, the use of short-range systems, increased use of higher frequencies, changing Federal spectrum needs, and (especially) the rapid growth of optical fiber systems. Though the benefits from these factors will not be immediately available, it is possible to project large long term (10-15 years) gains in spectrum capacity. The implication for IVHS is that sufficient spectrum should be available for future IVHS requirements.

KEY WORDS: IVHS, spectrum requirements, spectrum efficiency, spectrum shortage, frequency management

1. INTRODUCTION

The technical press is filled with stories of high growth rates and crowding in the cellular and land mobile radio (LMR) bands. Broadcasters wonder how to squeeze new high-definition television (HDTV) services into the existing TV bands. The Federal Communications Commission (FCC) reviews requests for new services requiring hundreds of MHz of new spectrum. These services include many types of personal communication services (PCS), direct broadcast satellites (DBS), mobile-satellite systems, wireless local area networks (WLANs), digital audio broadcasting (DAB), and more. Some of the Congressional bills which proposed to allocate additional spectrum to the private sector began with the assumption that there is a severe shortage of commercial radio frequencies. It is difficult to avoid the conclusion that a severe spectrum shortage will cripple many valuable entrepreneurial developments that might have produced great benefit for the U.S. economy.

This paper presents an alternative viewpoint: That long term spectrum crowding is not inevitable and that it could actually ease over the long term. I will make four main points:

1. The radio spectrum is a highly flexible medium, and the amount of service that can be extracted from a given part of it is generally much more than what is currently extracted. Spectrum is not a rigidly fixed, limited resource that needs to be rationed.

2. There have been major changes in the way spectrum is used. These include the massive shift to fiber optics (section 3) and a changing geopolitical environment (section 4).

3. New technologies are coming to practical fruition that allow much more efficient use of the radio spectrum. These include the use of higher frequency bands for consumer applications (section 5), short-range techniques that allow intensive re-use of frequencies (section 6), and digital signal compression (section 7).

4. IVHS has the time it needs to look carefully at its long term spectrum requirements. If IVHS has requirements that cannot be met in existing frequency bands, it should request additional frequency bands allocated by the FCC.

Cumulatively, the first three points show that there is no technical reason that a continually worsening frequency shortage should inevitably frustrate the introduction of new services. However, IVHS will still need to do its planning carefully and be continually alert to spectrum allocation opportunities to ensure that its services are adequately supported by radio frequencies.

2. SPECTRUM EFFICIENCY AND CAPACITY

Some people believe that there is a spectrum shortage because we are using more radio communication than ever before. This view assumes that it requires "X" bandwidth to send a message, and that if "Y" messages need to be sent, it will require a total bandwidth of "XY". If the total spectrum available is less than XY, there will be a spectrum shortfall and some messages cannot be sent. Therefore, people need to contend for spectrum, to make sure that their message is one of the messages that is sent.

A more correct view is that the amount of spectrum needed to send a message is dependent on the technology and architecture employed. We define the "capacity" of a given amount of spectrum as the ability to carry messages between users. Although a definition of absolute spectrum capacity or spectrum efficiency is difficult on a theoretical basis, a definition of "relative spectrum efficiency" is often simple and useful. Relative spectrum efficiency or relative spectrum capacity allows us to compare systems (or proposed systems). If System A carries the same message as System B, but requires only 1/Nth as much bandwidth as System B, we would say that System A has N times the spectrum efficiency as System B. We could also say that a portion of the radio spectrum had N times as much "spectrum capacity" when used by System A compared with System B.

The spectrum has no "natural" or inherent maximum capacity; it has capacity only in the context of use by a particular population of systems. A given radio channel (a lossy, bandwidth-limited RF link between a transmitting and receiving antenna pair) has information-carrying limits established by Shannon's Theorem. However, there are no obvious limits to the number of radio channels that can be established in a given geographical area. The total number of radio channels can be increased by using shorter channels, highly directional antennas, and higher frequencies--techniques which will be discussed later in the paper. The sum of the user messages that can be transmitted in the cumulative amount of bandwidth in the total number of radio channels represents the capacity of the spectrum.

Spectrum capacity is what is required when we send a message, not spectrum itself. If we need to send more messages, we can somehow obtain more spectrum or we can improve the spectrum capacity of the existing spectrum by using spectrum-efficient systems. A main point of this paper is that we have the means at hand to greatly increase the spectrum capacity of existing spectrum. The ratio of increased spectrum capacity is based on a comparison of the spectrum capacity of widely-used traditional systems with the spectrum capacity that would be possible if a reasonable number of future systems adopted efficient technologies. The increase in spectrum capacity is treated identically to an actual increase in spectrum, since a doubling of spectrum capacity gives the same increase in messages carried as a doubling of actual spectrum.

I will estimate a spectrum capacity improvement factor for each of several technologies and market shifts. Since these factors have been chosen to be independent of each other, the total increase in spectrum capacity is the product of all of the factors, not the sum of the factors. For example, a spectrum capacity factor of 3 due to digital compression and a spectrum capacity factor of 5 due to increased frequency for consumer products will give an increase in capacity of 15.

3. THE SHIFT TO OPTICAL FIBER

In the recent past, it was assumed that point-to-point microwave systems--along with some help from satellites--would carry the bulk of all long-range communications. More than half of the spectrum bandwidth below 30 GHz is allocated on a primary basis for this function. Extensive networks of microwave stations were built to span the United States. For many years these microwave networks carried the great majority of long-distance telephone calls, nationwide television programs, and data communications.

The development of optical fiber has changed the picture completely. A new communications paradigm is based partly on using fiber for most point-to-point long-haul communications, replacing many terrestrial and satellite microwave links. Fiber is an almost ideal information-carrying medium that does not require the use of any radio spectrum. A single commercial fiber can carry 2400 Mb/s with a loss of 0.3 dB/km. It is mechanically small and inert, can be buried to keep it out of harm's way, and is inherently passive and private. Typically, 20-30 fibers are included in a single cable to allow expansion for future uses.[1] By the end of 1992, more than 8 million fiber miles had been installed in the U.S., and the total is expected to continue growing 20-25% annually. Continued technological improvements will make future systems cheaper, higher capacity, more robust, and more widely available.

The replacement of microwave links with fiber is especially prevalent in the services where there is ample capital, high traffic density, and advantages in moving to all-digital systems. Long-distance telephone companies were the first to switch to fiber, with most of their fiber networks in place by the end of 1990. The local telephone companies are extensively converting to fiber now. The cable TV companies have announced extensive plans to convert much of their coaxial cable and their studio-toheadend microwave links to fiber over the next several years. Although many of the old microwave links continue in operation, there has already been a 20% drop in the total number of licenses in the 4 GHz, 6 GHz, and 11 GHz common carrier bands over the last few years.[2]

Fiber has also taken much traffic from satellites offering point-to-point services. A fiber path does not have the annoying delay caused by geosynchronous satellite relay of telephone calls, and fiber has completely replaced satellites for domestic telephone service. Transoceanic fiber systems are growing very rapidly today. Improved systems using optical amplifier/soliton technology over transocean distances have been tested in the laboratory at 10,000 Mb/s and are expected to capture much international telephone traffic from the transoceanic satellites. On the other hand, major growth is still expected for advanced TV broadcasting satellites (HDTV and DBS), for mobile-satellite services (maritime, aeronautical, and personal), and for point-to-multipoint very small aperture terminal (VSAT) services.

Growth in spectrum capacity reclaimed from bands emptied by fiber. The use of fiber means that many communication systems will never require any radio spectrum. In addition, I believe that some frequency bands now used for point-to-point long-haul microwave will be reallocated (probably for mobile services). This is already happening at 2 GHz, where fixed service bands are being reallocated to PCS.[3] The reallocation of bands vacated because of optical fiber will add 20% to the bandwidth of frequencies available for the rapidly growing mobile/PCS services. Therefore, the spectrum capacity increase factor due to fiber = 1.2.

4. CONVERSION FROM GOVERNMENT/MILITARY USE

In the United States about 11% of the spectrum below 30 GHz is allocated to the Federal Government, and another 35% is shared with Federal users. (The remaining 54% is exclusively allocated to non-Federal users.) There is a perception that the non-Federal frequency bands are more crowded than the Federal bands, partly because many Federal systems become active only during military training, war, natural disasters, or other special situations. Congress has recently passed a law that will require the Government to move 200 MHz of spectrum from Federal allocations to commercial use.[4]

The world military and political situation has changed dramatically in the last 10 years, and this will cause changes in U.S. military spectrum needs. The emphasis will be on a smaller, more mobile military, which might seem to have fewer spectrum needs. However, the new military will have even greater needs for excellent communications and intelligence. More extensive use of remote imaging and the need to support foreign operations in geographically diverse areas with fewer permanent foreign bases may actually expand the need for military communications.

Some improvement can be made in the way that military frequency uses are shared with civilian uses, without compromising the use for national emergencies. Certain civilian mobile radio systems in Britain, for example, can be "commandeered" for emergency/military use if the need arises. A military function used only on U.S. test and training ranges might be geographically shared with commercial users in large metropolitan areas. Frequency sharing may also be used to encourage the development of dual-use systems that could reduce the cost and increase the efficiency of a military system.

Many Federal telecommunication systems were originally built to provide needed communications when there were no alternative commercial services available. Thus, dozens of Federal agencies built hundreds of radio nets to support Rangers in remote areas of National Parks and Forests, to monitor military test ranges, to control air traffic, etc. The commercial telecommunications industry has grown tremendously since then and is now able to meet many more Government needs. The prospect of commercial mobile-satellite service and very flexible PCS services will increase the range of services available to Government. In Operation Desert Storm, the military made extensive use of commercial systems like Inmarsat, commercially available LAN computer networks, and civilian GPS receivers.

To encourage the transition to commercial services, Government programs (such as FTS 2000) require Federal agencies to use commercial telecommunication services whenever possible. Since the switch to commercial services is often not accomplished until an obsolete Federal network needs to be upgraded, this conversion will occur piecemeal over the next 10 to 20 years. The military has similar programs for the use of commercial services.

The shift from Government-provided communications affects the spectrum crowding problem in two ways. First, some special-purpose Federal communication systems (like many commercial private radio systems) are still tied to older inefficient technologies. The fragmented communication needs of single-agency systems do not encourage the large investment needed to build spectrum-efficient trunked or cellular systems. Therefore, switching to a commercial supplier (whose aggregated traffic allows an investment in fiber, cellular, or trunked radio) can make a substantial improvement in overall spectrum efficiency. Of course, some Federal agencies will continue to have special needs which will not be operationally or economically met by commercial systems.

Second, it is important to note that as Federal agencies make more extensive use of commercial systems, the resulting unused Federal frequencies should provide an opportunity for commercial development.

Increase in spectrum from Federal frequency bands. I believe that a substantial amount of Federal spectrum can eventually be given to or shared with commercial users, including the 200 MHz that Congress recently authorized. This spectrum would probably be allocated mostly to various mobile and PCS needs. Averaged across all current non-Federal, non-Fixed bands, this would increase available spectrum by 10%, giving a spectrum capacity factor of 1.1.

5. THE SHIFT TO HIGHER FREQUENCIES

Until recently, it was assumed that consumer products could not be built at frequencies above 1 GHz, due to the prohibitive cost of special construction techniques and expensive components. In the last few years, however, the number of radio frequency bands that can be practically and economically used for general purposes is rapidly expanding. There has been a continual improvement in the ability to economically produce complex gallium arsenide (GaAs) monolithic microwave integrated circuits (MMICs). Furthermore, a shift from long-range radio paths to short-range ones (see the next section) has meant that low-power transmitters will be sufficient for many purposes, so the lack of high-power MMICs will not be a major limitation.

Although a spectrum allocation chart for the U.S. shows designated allocations for all frequencies up to 300 GHz, there is not a large amount of actual usage at higher frequencies. Though there is not a well-defined demarcation between the sparsely used higher frequencies and the more heavily used lower frequencies, one can say that most frequency bands below 6 GHz tend to be more heavily assigned than those above 6 GHz. A few satellite bands, a few military and special-purpose radar systems, and recently developed short-range microwave bands at 18 GHz and 23 GHz constitute most of the usage one might actually see above 13 GHz. Below 1 GHz, most frequencies are heavily assigned and used by consumer broadcasting and mobile services.

Many consumer systems are being planned for frequencies above 1 GHz. The FCC has planned that PCS will be placed near 2 GHz. AT&T has announced PCS experiments at 6 GHz. Motorola has announced their "Altair" wireless LAN operating at 18 GHz. The FCC has re-allocated the 28 GHz band for "cellular cable" or Local Multipoint Distribution Service (LMDS) to deliver TV and other services to consumers. The U.K. recently allocated frequency bands at 38 GHz, 55 GHz, and 58 GHz for PCS and short-range communications.

Growth in spectrum capacity from use of higher frequencies. Although the frequency bands available to consumer uses have greatly increased (from 1 GHz to 28 GHz), the higher frequencies will still remain somewhat less used. In addition, non-consumer systems have been using these higher frequency bands for many years, though at lower concentrations of usage. Balancing these various factors, I expect the use of higher frequencies to increase spectrum capacity (averaged across all users and all frequency bands) by 5.

6. SHORT-RANGE SYSTEMS

Traditionally, radio provided long-range transportation of information. Short-wave transmitters could span oceans and reach where no other communications would go; the farther the signal would go, the better the radio system. Today, however, with the transport role handled by copper or optical fiber, radio can be optimized for short-range convenient access to information that is near at hand.

Short range means that the user can operate with lower transmitter power, providing longer battery life and smaller pocket-sized equipment. Short range lessens the disadvantages of increased path loss at higher frequencies and increased power requirements for wider bandwidths. Short range also provides the possibility of intensive frequency reuse, since the same frequency can be reused wherever a neighbor's use of that frequency does not intrude. One example of a short-range system is cordless telephones, where ten frequency pairs support about 50 million U.S. users.[5]

Industry has been developing a progression of smaller cell sizes for mobile systems, beginning with conventional mobile phone (30-mile service range), to cellular phone, to cellular phone with reduced cell size, to PCS service, to cordless phone (300-foot service range). In systems that define a cell as the coverage area from a single transmitter, frequencies can be re-used every two to four cell diameters. Therefore, the smaller cell sizes offer extensive re-use within the geographical area of a large city. Since the ability to re-use a frequency is just as valuable as obtaining a new frequency, small cells can provide an extraordinary increase in spectrum capacity.

On the other hand, small cells incur higher infrastructure costs because of the large number of cells needed and the increased complexity of the network connecting them. In addition, very small cells may have more difficulty in rapidly switching service between cells to follow a moving vehicle. Therefore, some services will continue to be provided with larger cell geometries, especially in rural areas where low traffic density will not support an expensive infrastructure.

Growth in spectrum capacity from short-range systems. The capacity of spectrum based on frequency re-use is inversely proportional to the coverage area of a cell, and area varies as r^2 (r = radius). A 300-foot-radius cordless phone system would be about 250,000 times more efficient than a 30-mile-radius mobile radio system, though many of tomorrow's systems will not be that efficient. There will be a continuing requirement for some longer-range mobile systems. Many types of systems, like point-to-point microwave, satellite, radar, and broadcasting systems cannot benefit from this type of range reduction. I expect a spectrum capacity improvement factor from improved frequency re-use (averaged across all frequencies and all uses) of 25.

7. DIGITAL SIGNAL-COMPRESSION TECHNIQUES

Voice and visual information represent the great majority of signals transmitted by radio. Both of these signal types contain a large amount of redundant information, however, and it is possible to transmit less data if the redundant information is stripped out. For example, a complete new TV picture is transmitted every 1/30 second, even though there is usually only a small change from the previous picture. An efficient compression technique would transmit only the information needed to describe the changes from the previous picture.

Unfortunately, the large amount of computer processing needed to perform the transmitter compression algorithms and the receiver de-compression made the process impractical, until recently. The development of very powerful digital signal processing (DSP) chips has made the techniques practical, and they have been selected for large-scale consumer applications in the near future.[6] These new systems include high-definition TV (HDTV) squeezed into a conventional TV channel, optical fiber cable TV systems providing 500 channels, satellite TV with 3 to 10 times more channels, low-quality video phone service over regular telephone lines, pay TV over modified phone lines, high-quality video-conferencing over fractional T-1 lines, 3 to 6 times increase in cellular telephone capacity, efficient multimedia presentations on CD-ROM disks, and many more. These products will completely dominate the consumer market in the next several years.

Compression technologies are expected to become ever more effective as DSP chips and algorithms are improved. An important trade-off in portable equipment is whether it takes more battery power to transmit the uncompressed signal or to run the DSP chips that compress and de-compress the data. Rapid improvement in DSP technology means that the advantage will fall more in the direction of compressing the signal and using less bandwidth.

Growth in spectrum capacity from signal-compression techniques. Commercial signal-compression techniques typically provide 10:1 bandwidth compression for video signals and 6:1 compression for voice signals. Given that: (1) these signals compose a large percentage of the present radio traffic, (2) compression techniques are predicted to be widely used, and (3) compression techniques are rapidly improving, I expect a spectrum capacity improvement factor from signal compression of 3.

8. SUMMARY OF SPECTRUM CAPACITY FACTORS

The previous sections have described some of the factors that are expected to produce additional spectrum or spectrum capacity. There are more factors that could generate additional spectrum capacity, such as trunking technologies, more precise modelling in frequency management decisions, the use of active interference avoidance in low-power bands, and market-based redistribution of under-used frequencies. In this section, however, I will consider only the cumulative effect of spectrum capacity factors discussed earlier:

a. Fiber optical spectrum reclamation	1.2
b. Federal/military frequency reclamation	1.1
c. Availability of higher frequencies	5
d. Frequency reuse/short-range systems	25
e. Digital compression techniques	3

Total increase in spectrum capacity = 1.2 x 1.1 x 5 x 25 x 3 = 495

The product of these factors gives an overall increase in spectrum capacity of 495. This means that within the next 10-15 years these factors are expected to give us the equivalent of 495 times the spectrum capacity that we have at present using traditional technologies. The number "495" with 3 significant figures implies much more precision than intended. A more realistic evaluation of error bounds would suggest a 50% chance that the overall gain in spectrum capacity will be within + /- 25% of the expected values. The degree to which extra spectrum capacity is generated will be paced by the degree to which it is needed to meet customer demands. It is still too soon to predict the growth rates for PCS and advanced cellular and wireless services, which will be major factors in the growth of spectrum capacity.

It is worth noting that the reclamation-based factors (a,b) increase spectrum capacity by 1.3, while the technology-based factors (c,d,e) increase spectrum capacity by 375. This suggests that technology improvement has much more payoff than a rigorous reclamation of frequencies from lower-priority users.

One may object to multiplying the factors together, since it is not likely that a single system could ever take maximum advantage of all factors. However, the factors were derived from a consideration of the average benefit of a factor (averaged across all applications), not from a maximum benefit. In fact, many of the systems being planned today benefit from multiple factors.

A more significant objection is that this paper looks mainly at increased spectrum capacity, without equally examining increased demand. This objection is valid, since crowding depends on both capacity and demand. However, the purpose of this paper is to provide some balance to the widespread publicity given to dire predictions of serious crowding based only on increased spectrum demand. Estimates of growth in demand are difficult to compare with growth in capacity, since additional demands are typically stated in terms of "X hundreds of MHz", rather than "Y thousands of voice links". This is understandable, since the frequency management process allocates spectrum, not spectrum capacity. Nevertheless, the predicted 495 times increase in spectrum capacity seems to be well in excess of the projected growth in spectrum demand.

The present spectrum crowding will not disappear immediately, since spectrum capacity is created only as new spectrum-efficient equipment is installed and used. In the mobile services, for example, there is a backlog of demand which cannot be met using the old technologies of the traditional mobile services. Refarming, PCS, and wireless technologies represent a tidal wave of spectrum capacity that is now on the horizon. Other services will experience growth in spectrum capacity at their own rate, until an overall improvement of about 500 is achieved 10-15 years from now.

Although technology will produce most of the new spectrum capacity, the frequency management process will need techniques to reclaim spectrum from bands where technology produces spectrum capacity greatly in excess of needs. These techniques might facilitate sharing between old and new services, ease the migration of existing users from portions of established bands, or establish means to reimburse existing users. Although it will always be necessary to choose between competing uses for spectrum, greatly increased spectrum capacity will allow many more uses to be accommodated, easing the spectrum crowding that is experienced in some bands.

9. CONCLUSION - IMPLICATIONS FOR IVHS SPECTRUM ACQUISITION.

The long-term growth in spectrum capacity means that IVHS can (and should) take the time to realistically assess its spectrum requirements, expect to be able to place many IVHS functions within current band allocations, and confidently request additional spectrum for IVHS for applications not supported by current allocations. Because of the present frequency shortages, it will be prudent to be aware of any frequency allocation opportunities that might provide frequencies needed immediately for IVHS.

The development of plans for IVHS capabilities, architecture, and implementation strategy is a very high priority, because much other progress will depend on these plans. Architectural and administrative frameworks need to be determined before it can be known whether IVHS functions will be locally controlled using spectrum shared with existing non-IVHS services, whether large portions of IVHS infrastructure will be under direct Federal or State control using exclusive IVHS spectrum, or whether a mix of these concepts will be used. Since IVHS spectrum requirements depend strongly on these plans, it may be difficult to justify the acquisition of large amounts of spectrum until these plans are developed.

As shown by the July 1993 TRB "Spectrum Needs for IVHS" Workshop[7], the total IVHS requirements may not be huge, and many requirements could be met using services that are already allocated. Cellular telephone, cellular data services, FM subcarrier data, and planned personal communication services (PCS) can provide links with the vehicle. Fixed point-to-point services can be used for closed-circuit TV and data links to sensors and infrastructure. Allocated radar bands can be used for planned collision-avoidance radars. New allocations may be needed for IVHS functions without existing counterparts, such as systems for total vehicle guidance, as well as for services where IVHS systems demand more capacity than is available in existing bands. Most problems of IVHS spectrum acquisition are not acute, however, and they will probably get better, not worse.

There may be an additional benefit in not freezing IVHS spectrum needs prematurely. The general societal shift from fixed radio services to mobile/personal services is causing rapid development of new mobile data technologies, which may meet IVHS long-term requirements better than current technologies. For example, broadband digital audio broadcasting (DAB) and/or a coded orthogonal frequency-division multiplexed (COFDM)[8] version of HDTV may provide the best technologies for transporting broadband digital information to moving vehicles. Similarly, a new mobile satellite service might be the best way to relay "mayday" and other emergency messages.

Using technology that is available today, we can reasonably expect a 500-fold increase in spectrum capacity. Although we expect a continued rapid increase in demand for spectrum-based services, I believe that technology will continue to expand capacity to surpass the increased demand.

BIOGRAPHICAL DATA ON ROBERT J. MATHESON

Mr. Matheson has degrees in Physics and Electrical Engineering from the University of Colorado, and is a member of IEEE. He began his 35-year career with the Federal Government making environmental radio noise measurements. He spent 15 years leading the NTIA radio monitoring program, which provided spectrum occupancy data and technical measurements in support of NTIA's Federal frequency management responsibilities. Following 3 years as Deputy Director of the Spectrum Division of the Institute for Telecommunication Sciences (a research arm of NTIA), he has continued to work at ITS studying the use of the Fixed and Mobile Services in the U.S. This work is aimed at trying to get a handle on "the big picture" in spectrum crowding.

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